NASA-CR-202813

Numerical Computation of Flame Spread over a Thin Solid in Forced Concurrent Flow with Gas-Phase Radiation

Ching-Biau Jiang and James S. T'ien
Department of Mechanical and Aerospace Engineering
Case Western Reserve University
Cleveland, Ohio

I. Introduction

Concurrent-flow flame spread over a thin solid in purely forced flow with gas-phase radiation is examined numerically. The computational model solves the two-dimensional, elliptic, steady and laminar conservation equations for mass, momentum, energy, and chemical species (oxygen, fuel, carbon dioxide, and water vapor). Gas-phase combustion is modeled via a one-step, second order finite rate Arrhenius reaction. Gas-phase radiation considering gray non-scattering medium (CO_2 and H_2O) is solved by S-N discrete ordinates method. A simplified solid phase treatment assumes a zeroth order pyrolysis relation and includes radiative interaction between the surface and the gas phase.

The formulation in this work is similar to that in [1] except that we have included gas-phase radiation. It has been shown that in low-speed flows [2, 3] that gas-phase radiation is amplified and can become important in the flame energy balance. The solution procedure is also different from that in [1] in that the entire flame domain is solved using elliptic equations rather than the mixing elliptic-parabolic approach used in [1].

The flame configuration is shown schematically in Fig. 1. The coordinates are fixed with respect to the fuel burnout point ($x = y = 0$) and steady state solutions are sought. The equation of transfer for radiation is solved by S-N discrete ordinates method [4, 5, 6]. An evaluation has been made which reveals that one-dimensional S_2 scheme (2 ordinates) and two-dimensional S_2 scheme (4 ordinates) give poor accuracy for the radiative flux, but the difference between two-dimensional S_4 scheme (12 ordinates) and two-dimensional S_6 and S_8 schemes (24 ordinates and 40 ordinates, respectively) is small. Consequently, the two-dimensional S_4 scheme is chosen to simulate gas-phase radiation based on the balanced consideration of numerical accuracy and computational cost.

II. Results and Discussion

In this section, we will present selected results of a purely forced, concurrent-flow spreading flame with gas-phase radiation at 15% O_2, $U_\infty = 6$ cm/sec. The properties chosen are the same as those in Ref. 1. Comparison with the results neglecting gas radiation will also be made.

Fig. 2 shows nondimensional radiation heat flux vectors (nondimensionalized by σT^4_∞). It reveals the multidimensional characteristics of radiation. The net radiation heat flux vectors all point outward, meaning heat is lost from solid fuel and flame zone to ambient. Fig. 3 shows contours of nondimensional $\nabla \cdot q_r$ term in the energy equation (nondimensionalized by $\sigma T^4_\infty/\delta$, where δ is thermal diffusion length). Because the flame is optically thin, little absorption takes place and the $\nabla \cdot q_r$ term is positive which implies local heat loss.

In the rest of this paper, we will compare the flame structures of corresponding cases with and without gas radiation. Fig. 4 shows nondimensional temperature contours (nondimensionalized by T_∞). Fig. 5 shows fuel reactivity contours. Comparing the cases in Fig. 4 and Fig. 5, we see that the flame temperature decreases and flame size shrinks when gas radiation is included. A similar finding was reported in opposed-flow flame spreading [2, 7]. Fig. 6 gives the solid fuel surface heat fluxes from conduction (convection) and radiation and the summation of the two. It shows that conduction heat flux is lowered when gas radiation is included since flame temperature decreases. The net radiation flux is negative indicating heat loss from solid surface. However, the loss in gas radiation case is less than that when gas radiation is neglected. This is because with part of the gas radiation is absorbed by solid fuel. The competition of the conductive heat gain and the radiative heat loss results in approximately equal net heat flux to the solid fuel for the two cases. As a result, the flame spread rates are almost equal (0.38 cm/sec with gas radiation vs. 0.42 cm/sec without gas radiation), despite the large difference of gas phase flame structure. It should also be pointed out that because of the flame temperature decrease, the computed condition (15% O_2, 6 cm/s) is a near-limit flame (5 cm/s is not flammable) when gas radiation is included. The same condition is well within the flammable domain when gas radiation is ignored [1].

Acknowledgment

This research has been supported by the NASA Microgravity Science and Applications Division through Grant NAG 3-1046.

References

1. Ferkul, P.V. and T'ien, J. S.: A Model of Low-Speed Concurrent Flow Flame Spread over a Thin Fuel, Combst. Sci. and Tech., to appear.
2. Bhattacharjee, S. and Altenkirch, R.A.: Radiation-Controlled, Opposed-Flow Flame Spread in a Microgravity Environment, Twenty-Third Symposium (International) on Combustion/The Combustion Institute, pp. 1627-1633, 1990.
3. Rhatigan, J. and T'ien, J. S.: Gas-phase Radiative Effects on the Burning of a Solid Fuel, Eastern States Meeting, The Combustion Institute, Princeton, 1993.
4. Chandrasekhar, S.: Radiative Transfer, Dove Publications, Inc., New York, pp. 149-150, 1960.
5. Fiveland, W. A.: Discrete Ordinates Solutions of the Radiative Transfer Equation for Rectangular Enclosures, Journal of Heat Transfer, Vol. 106, pp. 699-706, 1984.
6. Kim, T. K. and Lee, H. S.: Radiative Transfer in Two-Dimensional Anisotropic Scattering Media with Collimated Incidence, Journal of Quantitative Spectroscopy and Radiative Transfer, Vol. 42, pp. 225-238, 1989.
7. Chen, C. H. and Cheng, M. C.: Gas-phase Radiative Effects on Downward Flame Spread in Low Gravity, Combust. Sci. and Tech., Vol. 97, pp. 63-83, 1994.